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Extinction in the Galaxy from surface brightnesses of ESO-LV galaxies: testing 'standard' extinction maps

Jacek Chołoniewski,[1] Edwin A. Valentijn[2]
[1] *Astronomical Observatory of Warsaw University, Aleje Ujazdowskie 4, PL-00478 Warsaw, Poland, e-mail: astro@estymator.com.pl*
[2] *Kapteyn Institute, P. O. Box 800, NL-9700 AV Groningen, The Netherlands, e-mail: valentyn@astro.rug.nl*

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ABSTRACT
The relative extinction in the Galaxy computed with our new method (Chołoniewski & Valentijn 1999, CV) is compared with three patterns: Schlegel, Finkbeiner & Davis (1998, SFD), Burstein & Heiles (1978, BH) and the cosecans law. It is shown that extinction of SFD is more reliable then that of BH since it stronger correlates with our new extinction. The smallest correlation coeffcient have been obtained for the cosecans law. Linear regression analysis show that SFD overestimate the extinction by a factor of 1.4.

Our results clearly indicate that there is non-zero extinction at the Galactic South pole and that the extinction near the Galactic equator ($|b| < 40^o$) is significantly larger in the Southern hemisphere than in the Northern.

Key words: dust, extinction - methods: statistical - Galaxy: general - galaxies: fundamental parameters

1 INTRODUCTION

We have introduced in our previous paper (Chołoniewski & Valentijn 1999, hereafter CV) a new method for the determination of the extinction in our Galaxy. The method uses surface brightnesses of external galaxies in the B and R bands as listed in *The Surface Photometry Catalogue of the ESO-Uppsala Galaxies* (Lauberts & Valentijn, 1989, hereafter ESO-LV). The first draft of this method has been published in our earlier paper (Chołoniewski & Valentijn 1991).

The main purpose of the present paper is to compare our derived extinction values with recently published maps of extinction by Schlegel, Finkbeiner & Davis (1998), hereafter SFD, and with the frequently used map of Burstein & Heiles (1978), hereafter BH (see also Burstein & Heiles 1982).

2 THE METHOD

Our extinction determination (fully described in CV) employs the surface brightnesses of external galaxies in the B and R bands: μ_B, μ_R. Basically, our method produces the relative extinction compared to an overall mean - extinction with an *unknown zero-point*. The formula for the relative extinction (in B band) is simply a linear combination of μ_B and μ_R:

$$A_B = \frac{\mu_B - s\ \mu_R}{1 - r\ s} - c. \qquad (1)$$

In order to use equation (1) one has to know three parameters: r, s and c.

The parameter r describes the ratio of extinction in the R and the B band ($r = A_R/A_B$) and is assumed to be constant. Its recent literature value is 0.61 (see CV for references) while we derived in CV two new estimates: 0.62 and 0.64. As a reasonable compromise we adopt throughout this paper $r = 0.62$.

The inverse of the parameter s describes the slope of the linear relation between surface brightnesses μ_B and μ_R. The c parameter is introduced in order to maintain zero-point issues. Both parameters s and c depend on morphological type T, so they have been computed (using equations 7 and 10 in CV) separately for every morphological type.

In this paper we will consider several different subsamples. Extinction within every such subsample has been computed using the set of values $s(T)$ and $c(T)$ obtained from the same set of data. The $s(T)$ and $c(T)$ coefficients for the most important two subsamples used in ths paper are in Table 1.

We use in this paper the extinction in B band as described in equation (1) and denote it as $A_B(CV)$.

3 THE SAMPLES

For our analysis we use *surface brightnesses at the radius of half total B light* in B and R bands from ESO-LV. We exclude from the sample those galaxies which have morphological

Table 1. Coefficients $s(T)$ and $c(T)$ used for computing relative extinction in this paper according to equation 1

	sample "A"		sample "B"	
T	s(T)	c(T)	s(T)	c(T)
-5	0.826	10.706	0.842	10.233
-4	0.955	6.263	0.997	4.199
-3	0.915	7.619	0.932	6.927
-2	0.893	8.295	0.894	8.306
-1	0.785	11.597	0.772	12.060
0	0.768	12.060	0.840	10.129
1	0.728	12.972	0.737	12.885
2	0.691	13.903	0.681	14.166
3	0.670	14.223	0.668	14.321
4	0.652	14.589	0.650	14.663
5	0.635	14.979	0.637	14.943
6	0.641	14.943	0.697	13.627
7	0.717	13.163	0.714	13.251
8	0.731	12.844	0.721	13.181
9	0.744	12.656	0.784	11.446
10	0.795	11.054	0.806	10.675

classifications suspected to be extinction dependent (marked in ESO-LV with T_{flag} equal to 4). We also reject galaxies which have excessive (probably wrong) colours: $\mu_B - \mu_R$ smaller than zero or greater than 2.1.

Since we focus in this paper on the comparison of our extinction with SFD and BH data, we reject additionally those galaxies for which BH or SFD extinction values are not available.

The largest complete subsample of galaxies of ESO-LV can be made by selecting galaxies which have *visual apparent diameter* D_{org} greater or equal to 60 arcsec. It contains, after applying the rejections described above, 7974 galaxies (sample "A").

As mentioned in CV, the completeness limit of ESO-LV galaxies is morphological type dependent and a universal criterion, valid for every morphological type, is selecting galaxies with a visual diameter limit larger than 100 arcsec. We have used such more restricted sample for all the computations presented in CV. We use it also here as sample "B" (after rejections described above).

Results described in Sections 4 and 5 show that more rigorousely defined sample "B" produces slightly more accurate extinction *per galaxy* than the sample "A". However the sample "A" is three times larger than the sample "B" what, at least in part, compensate its slightly larger dispersion.

Table 2 contains a summary of the definitions of sample "A" and sample "B".

Since the ESO-LV galaxy catalogue covers the Southern sky ($\delta < -17.5^o$) our analysis refers to this part of the hemisphere.

4 THE ACCURACY

Equation (1) represents an estimator of the foreground relative extinction for an individual external galaxy. It is important to know its uncertainty (standard error). In order to obtain this, we have divided the whole sky into squares with size Δ degrees and computed the average variance of the extinction inside these squares using the formula given by the so called one-way analysis of the variance theory (see e. g. Fish 1962). This average variance reflects the variations of the true extinction inside the squares with size Δ and the standard error of the extinction estimator expressed in equation (1). So, when the size of the squares Δ tends to zero the average variance of the extinction should tend to the standard error of the extinction produced by our method.

Figure 1 shows the average variance of extinction as a function of Δ. The minimum value for Δ which we applied was one degree. For smaller values of Δ a too large fraction of studied squares contain only one galaxy (such squares can not be taken into account in the one-way analysis of variance).

As we expect, the average variance has minimum for the smallest applied value of Δ (one degree). For sample "A" the standard error of our extinction in A_B is 0.43 magnitude, while for sample "B" this is 0.40 magnitude, which corresponds to a standard error in $E(B-V)$ of approximately 0.10 magnitude (for $A_B/E(B-V) = 4.3$). Sample "B" produces relative extinction with slightly higher accuracy than sample "A".

BH used for the calibration of their extinction map B-V colours of 131 globular clusters and RR Lyrae stars. SFD used for the calibration of their extinction map B-R colours of 106 brightest cluster ellipticals and B-V colours of 389 elliptical galaxies with measured Mg_2 index (505 objects in total).

Both BH and SFD report that their calibrators show a residual scatter in B-V, with respect to calibration regression line, of approximately 0.03 magnitude.

Our extinction estimator, when applied to photographically measured surface brightnesses of galaxies in two bands as listed in the ESO-LV catalogue, has three times larger standard error than the calibrators used by BH and SFD. This is an important disadvantage (at least as long as we apply it to ESO-LV photometrical data). But there is one important advantage of our extinction estimator - it can be applied to many more objects since we can apply the method, at present, to 7974 galaxies (sample "A") from the ESO-LV catalogue.

Table 2. Definitions of the galaxy samples.

General conditions:

$A_B(BH)$ - present
$A_B(SFD)$ - present
$T_{flag} \neq 4$
$0 \leq \mu_B - \mu_R \leq 2.1$

sample A	sample B
$D_{org} \geq 60\, arcsec$	$D_{org} \geq 100\, arcsec$
N=7974	N=2450

5 THE CORRELATION

We have computed the Pearson, Spearman and Kendall correlation coefficients (see Press, Teukolsky, Vetterling & Flannery 1992 for definitions and software) between our extinc-

Table 3. Pearson, Spearman and Kendall correlation coefficients between $A_B(CV)$ extinction estimate and three other extinction estimates: SFD, BH and csc(b).

	Pearson	Spearman	Kendall
Sample "A"			
SFD	0.276	0.234	0.158
BH	0.247	0.219	0.148
csc(b)	0.202	0.188	0.127
Sample "B"			
SFD	0.327	0.304	0.208
BH	0.293	0.282	0.192
csc(b)	0.238	0.252	0.170

tion and extinction given by SFD and BH and for the cosecans law:

$$A_B = A_0 \csc|b|, \quad (2)$$

where b denotes Galactic latitude. The computation have been performed for sample "A" and sample "B" (see Table 3). The parameters $s(T)$ and $c(T)$ have been computed separately for every sample (see Table 1).

All three correlation coefficients for both samples are the largest for SFD extinction and the smallest for the cosecans law. The extinction of BH is always between these two extreme results.

The coefficients are generally higher for sample "B" than for sample "A" what suggests that sample "B" produces more accurate extinction than sample "A".

Since the sample "B" is a subsample of the sample "A" the correlation coefficients for "A" and "B" are not statistically independent. In order to produce a set of statistically independent correlations we divide the sample "A" into six subsamples:

(i) $60\,arcsec \leq D_{org} < 80\,arcsec$ (N=3876)
(ii) $80\,arcsec \leq D_{org} < 100\,arcsec$ (N=1648)
(iii) $100\,arcsec \leq D_{org} < 120\,arcsec$ (N=718)
(iv) $120\,arcsec \leq D_{org} < 140\,arcsec$ (N=647)
(v) $140\,arcsec \leq D_{org} < 160\,arcsec$ (N=298)
(vi) $160\,arcsec \leq D_{org}$ (N=787) ,

and compute the parameters $s(T)$ and $c(T)$ separately for every subsample. As a result of this procedure we have six statistically independent correlation coefficients - see Figs 2, 3 and 4 for results. As before, the correlations are the largest for SFD, smaller for BH and the smallest for cosecans law.

6 CORRECTION OF THE BH'S EXTINCTION ZERO POINT

The formulae of BH produces for some regions of the sky extinction less than zero (for the samples analyzed in this paper the minimum value of $A_B(BH)$ extinction is -0.12 magnitude). In spite of BH's instructions to set these values to zero we have actually used these negative values and found that $A_B(CV)$ is for them significantly smaller than for $A_B(BH) \approx 0$ (see upper panel of Figs 7 and 8). This means that the BH extinction (in the B band) was underestimated by 0.12 magnitude - just the absolute value of the minimum value of $A_B(BH)$ extinction. This is in approximate agreement with SFD who discovered a similar offset of 0.09 magnitude. We use in the regression analysis presented in the next Section the corrected BH's extinction: $A_B(BH)_C = A_B(BH) + 0.12$ instead of $A_B(BH)$ itself.

7 THE LINEAR REGRESSION

In the ideal case there would be linear dependence with slope equal to one between our relative extinction estimate (CV) and the extinction of SFD and BH (corrected).

Since our extinction values are relative, with an arbitrary zero-point, the constant term of this linear dependence should not be equal to zero. The constant, multiplied by -1, should be added to our *relative* extinction to transform it to the *absolute* extinction.

We have fitted the straight lines (using the least squares method) taking as independent variables extinction of SFD and BH and as dependent variable our estimate of relative extinction (CV). We have found the following regression coefficients for sample "A":

$$A_B(CV) = 0.662\,(\pm 0.028) A_B(SFD) - 0.189\,(\pm 0.010) \quad (3)$$

$$A_B(CV) = 0.555\,(\pm 0.026) A_B(BH)_C - 0.176\,(\pm 0.010) \quad (4)$$

and for sample "B":

$$A_B(CV) = 0.741\,(\pm 0.043) A_B(SFD) - 0.225\,(\pm 0.016) \quad (5)$$

$$A_B(CV) = 0.608\,(\pm 0.040) A_B(BH)_C - 0.206\,(\pm 0.017) \quad (6)$$

where in brackets 1σ errors are given. The differences between slopes and constant terms computed for sample "A" and "B" are only marginally larger than the combined errors. In the forthcoming we use their averages.

A graphical presentations of the regression lines are shown in Figs 5-8. In order to investigate whether the postulate about linear dependence is valid, the regression lines are shown together with row data (lower panels) and with averages of $A_B(CV)$ computed for 0.05 magnitude bins of $A_B(SFD)$ and $A_B(BH)$ (upper panels).

The slopes of the regression lines are definitely less than one: for SFD the slope is circa 0.7 while for BH it is circa 0.6. The constant terms for both SFD and BH are approximately the same: -0.20 magnitude. This defines the zero point of our results: adding 0.20 magnitude to our *relative* extinction transforms it to the *absolute* extinction.

When we introduce our absolute extinction into equations 3 - 6, the constant terms in all 4 equations gets close to zero, now setting the relation between our (absolute) extinction and SFD's and BH's extinction. Thus we conclude: SFD overestimate extinction by a factor of $0.7^{-1} \approx 1.4$ while BH by a factor of $0.6^{-1} \approx 1.7$.

Up to now five papers reported similar results, namely: that SFD extinction is about 1.4 times too large. Stanek (1998b) obtained, using colours of low galactic latitude globular clusters, that the overestimation factor is 1.35 (see also Stanek 1998a). Arce & Goodman (1999a, 1999b) analyzed extinction in the Taurus region using four independent methods and found that the factor is 1.3 - 1.5. Gonzalez, Fruchter & Dirsch (1999) obtain extinction in the small field around GRB 970228. They found using two methods $A_V = 0.55$ while $A_V(SFD) = 0.78$. The ratio of these two

numbers give again a factor 1.4. Our finding that SFD overestimate extinction is also supported by Ivans et al. (1999) and von Braun & Mateo (2001).

Some kind of doubt about the correctness of the calibration is also in original SFD paper where we can find as the comment to their Fig. 6 the statement that "A slight trend in the residuals is evident for both BH and DIRBE/IRAS corrections, in the sense that the highest reddening values appear to be overestimated".

Inspecting Figs 5-8 demonstrate a general linear dependence between our relative extinction estimate and the extinction of SFD and BH. However, some minor, but statistically significant, deviations are clearly present, especially for $A_B(SFD)$ and $A_B(BH)$ less than 0.5 magnitude.

8 GALACTIC LATITUDE DEPENDENCE

Unfortunately, we can not use our method of extinction determination, as applied to the ESO-LV galaxy catalogue, to produce a new high resolution extinction map and to compare it with SFD and BH maps. This is because our data are too sparse (less than one galaxy per square degree) and their accuracy is too low ($\sigma(E(B-V)) \approx 0.10$ per galaxy) mainly because of instrinsic scatter of the surface brightness of galaxies.

But the quality of our data is good enough to evaluate their galactic latitude dependence. We show this dependence for our absolute extinction (equal to the relative extinction, as defined in equation 1, plus 0.20 magnitude) together with SFD, corrected BH and the cosecans low - see Fig. 9. All four solutions have been averaged inside 5 degrees galactic latitude bins in the points where ESO-LV galaxies are (sample "A"). We use $A_o = 0.10$ for the cosecans law (equation 3) to match as close as possible to our solution.

Fig. 9 shows that our absolute extinction is always greater than zero confirming the value of the zero-point computed in Section 7.

As one can see in Fig. 9 our solution as well as SFD and BH mimic quite well the classic cosecans law and indicate considerable extinction near the galactic pole. The differences between our results and SFD and BH are the largest near the galactic equator and at the northern hemisphere.

Since we find that both SFD and the (corrected) BH extinction standards overestimate Galactic extinction by a factor 1.4 and 1.7 respectively, we show the same data as in Fig.9 but with SFD and corrected BH extinction divided by these factors (or, equivalently, multiplied by 0.7 and 0.6 respectively) - see Fig. 10. The better agreement of our solution with the rescaled SFD and BH data is evident, especially near the Galactic equator ($b \approx 0$), confirming the need for rescaling SFD and BH extinction. But even for the rescaled data statistically significant differences between our results and SFD and BH, although smaller, still exist. Especially our data exhibit a South - North asymmetry near the galactic equator ($|b| < 40^o$) with more extinction in the Southern Galactic hemisphere which is not visible in SFD and BH data.

9 DISCUSSION

Our extinction estimator (introduced in CV) definitely indicates that the new extinction map of SFD is more realiable than the old one of BH. The historical cosecans law is in this competition on the last place. This result has been obtained using six separate, statistically independent, sets of data.

The superiority of the SFD extinction map over the BH map have been demonstrated by computing correlation coefficients with our extinction results. However, the correlation coefficients are not sensitive to the amplitude of variation of the input data nor its zero-point. In order allow for further, more specific, comparisons we have performed a linear regression analysis between our relative extinction and SFD's and BH's extinction. This analysis provides us the zero-point of our extinction (equal to 0.20 magnitude) which allows us to transform our relative extinction into absolute extinction. We have showed that, in comparison to our absolute extinction, SFD overestimate extinction by a factor of 1.4. This is in agreement with five other authors and considerably changes our view on the amplitude of the Galactic extinction.

Superiority of SFD over BH reddening map, as we report in this paper, does not mean that the first is an ideal result - we have discovered some significant differences between our extinction and SFD when analyzing their Galactic latitude dependence even after correcting SFD extinction by dividing it by 1.4 factor. One possible source of these differences is that SFD assume that the extinction is strictly proportional to the dust column density what need not be true - the extinction to dust ratio can vary across the sky and may also depend on the wavelength.

Our results are important for creating reliable extinction standards and demonstrate the correctness and usefulness of our extinction estimator. They can be also regarded as a stimulus for applying our extinction estimator to other, larger and more accurate galaxy catalogues, particularly thoose expected from new wide field imaging surveys,

Future applications of our method to other databases may produce maps with a courser resolution. At present the method applied to ESO-LV data is unable to generate the extinction map with both sufficient resolution and accuracy. Our present method should be rather taken as new extinction calibrator. But using the method to larger and more precise galaxy catalogues may result into stand-alone high resolution extinction maps.

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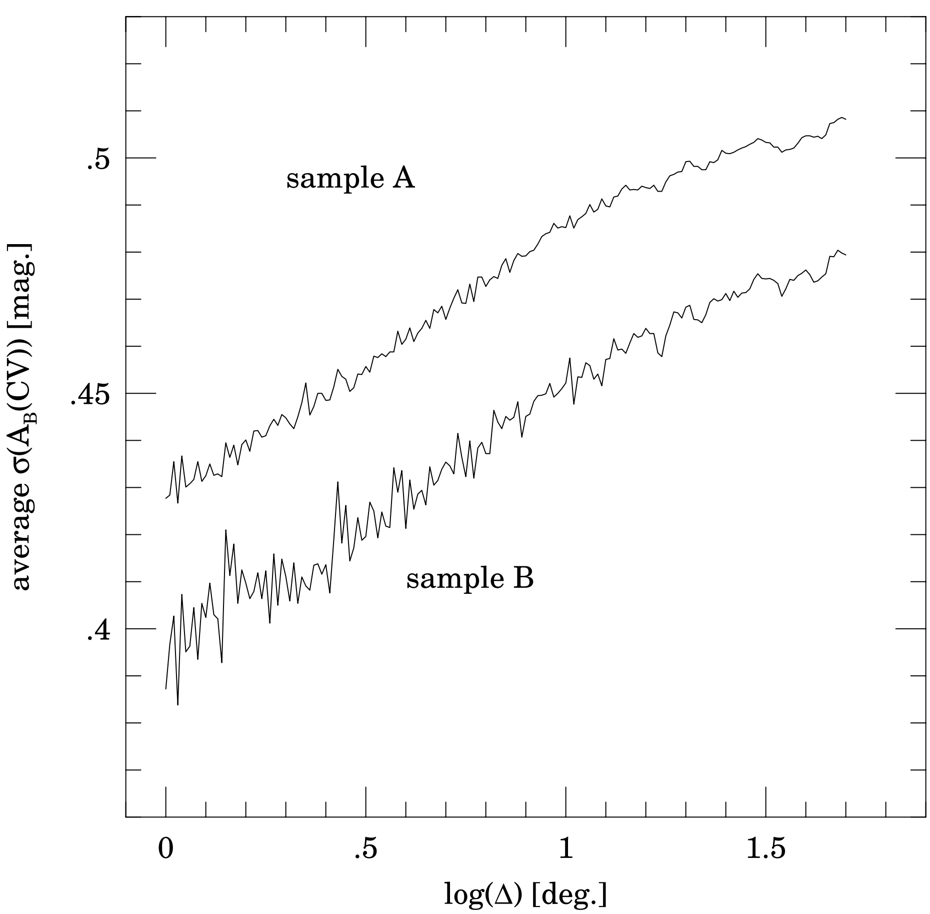

Figure 1. The average variance of extinction $A_B(CV)$ inside Δ degrees squares on the sky as a function of the size (Δ) of these squares. The minimum variance (at one degree: $log(\Delta) = 0$) represent the standard deviation of the estimator of relative extinction used in this paper.

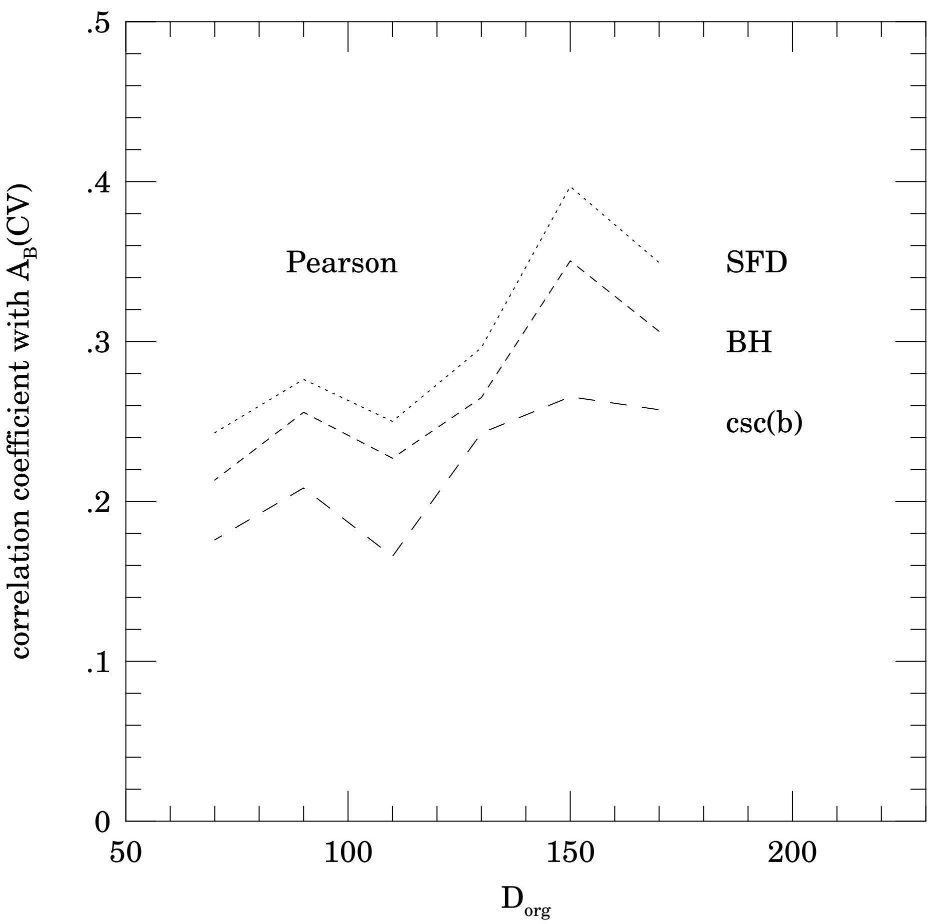

Figure 2. Pearson correlation coefficient between our $A_B(CV)$ extinction and the extinction of SFD and BH and the cosecans law computed for six subsamples defined using visual diameter D_{org} (see Section 5 for details)

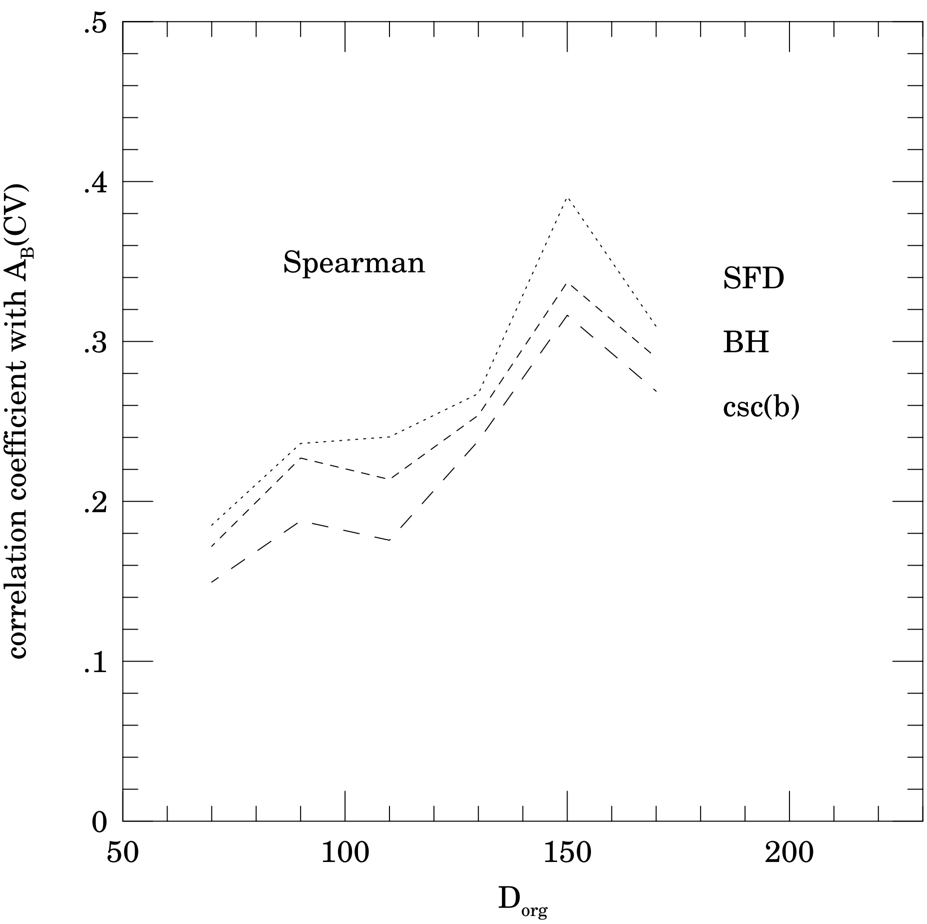

Figure 3. The same as Fig. 2 but for Spearman correlation coefficient.

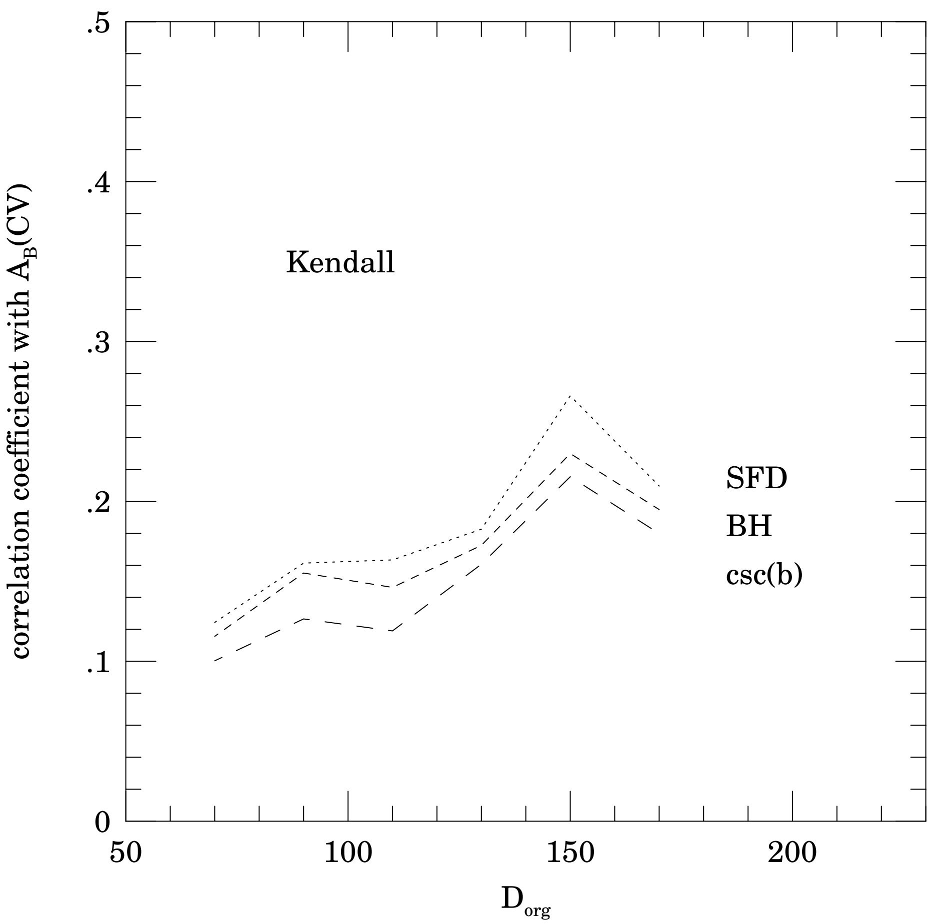

Figure 4. The same as Fig. 3 but for Kendall correlation coefficient.

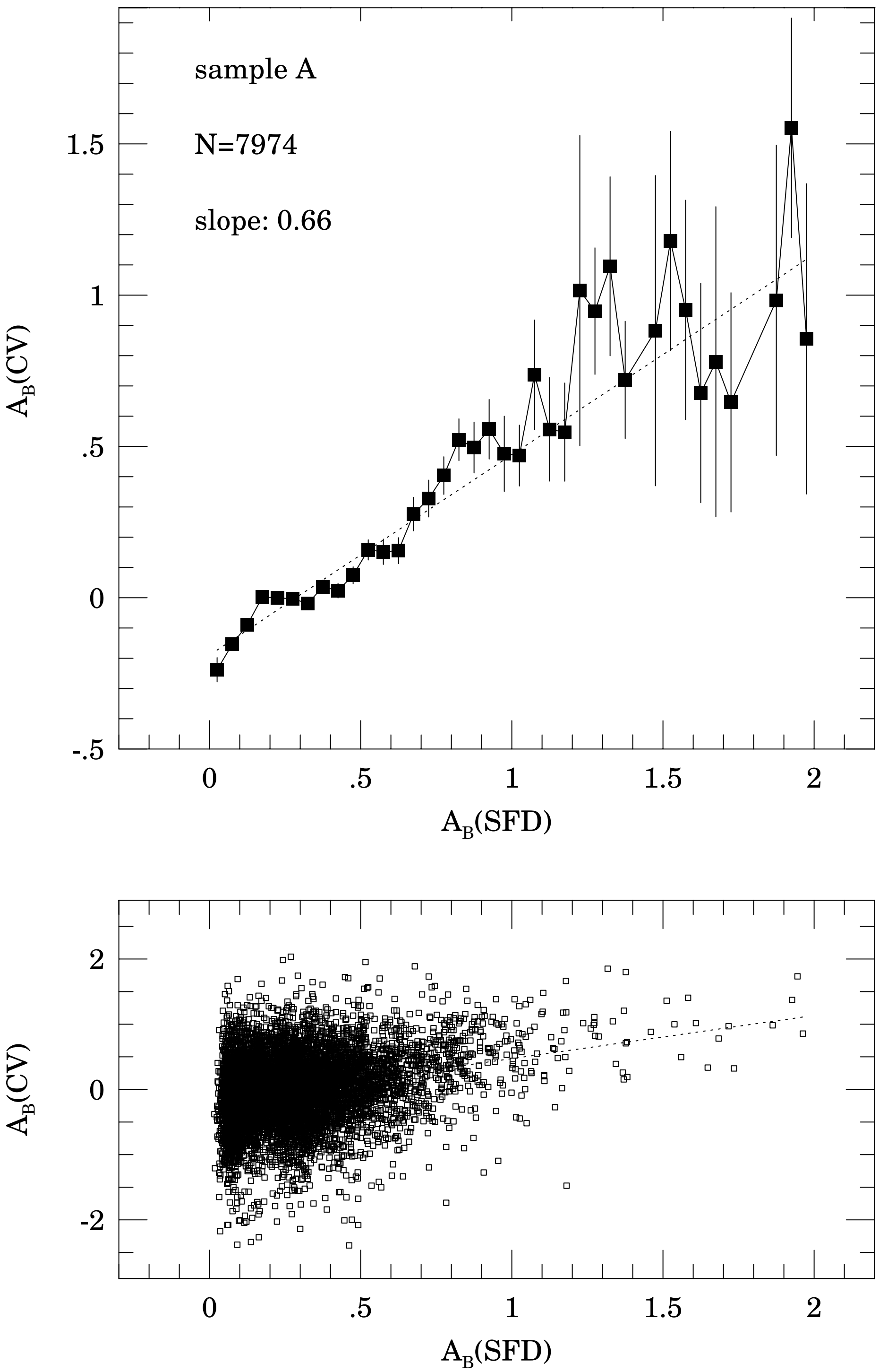

Figure 5. The dependence between the extinction of SFD $A_B(SFD)$ and our relative extinction $A_B(CV)$. Upper panel shows the averaged data inside 0.05 magnitude bins. Error bars represent standard deviation (1σ). Lower panel shows raw data. The data are taken from sample "A" (see text). Dotted straight lines visible on both panels represent the least squares fit.

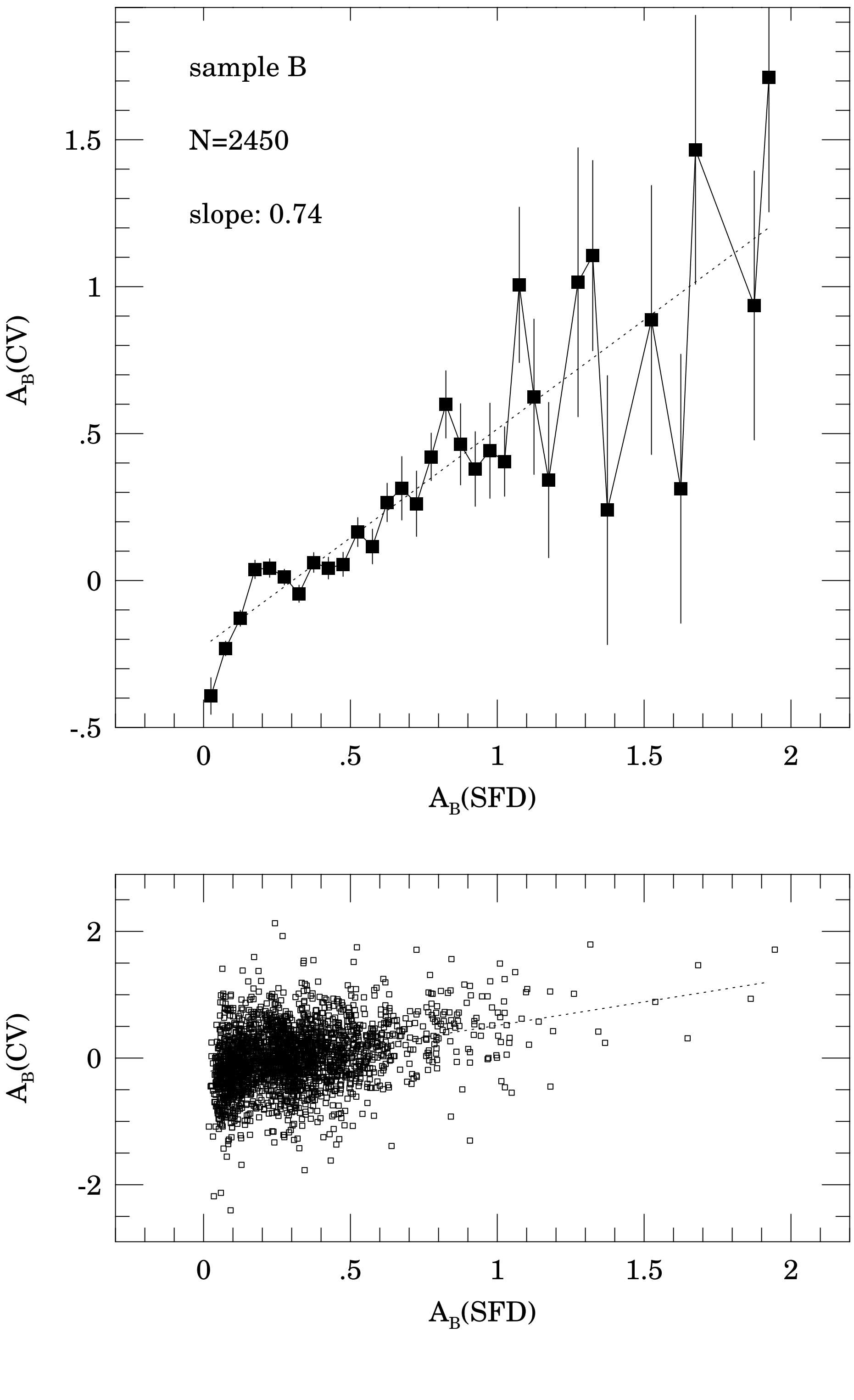

Figure 6. The same as Fig. 5 but for sample "B".

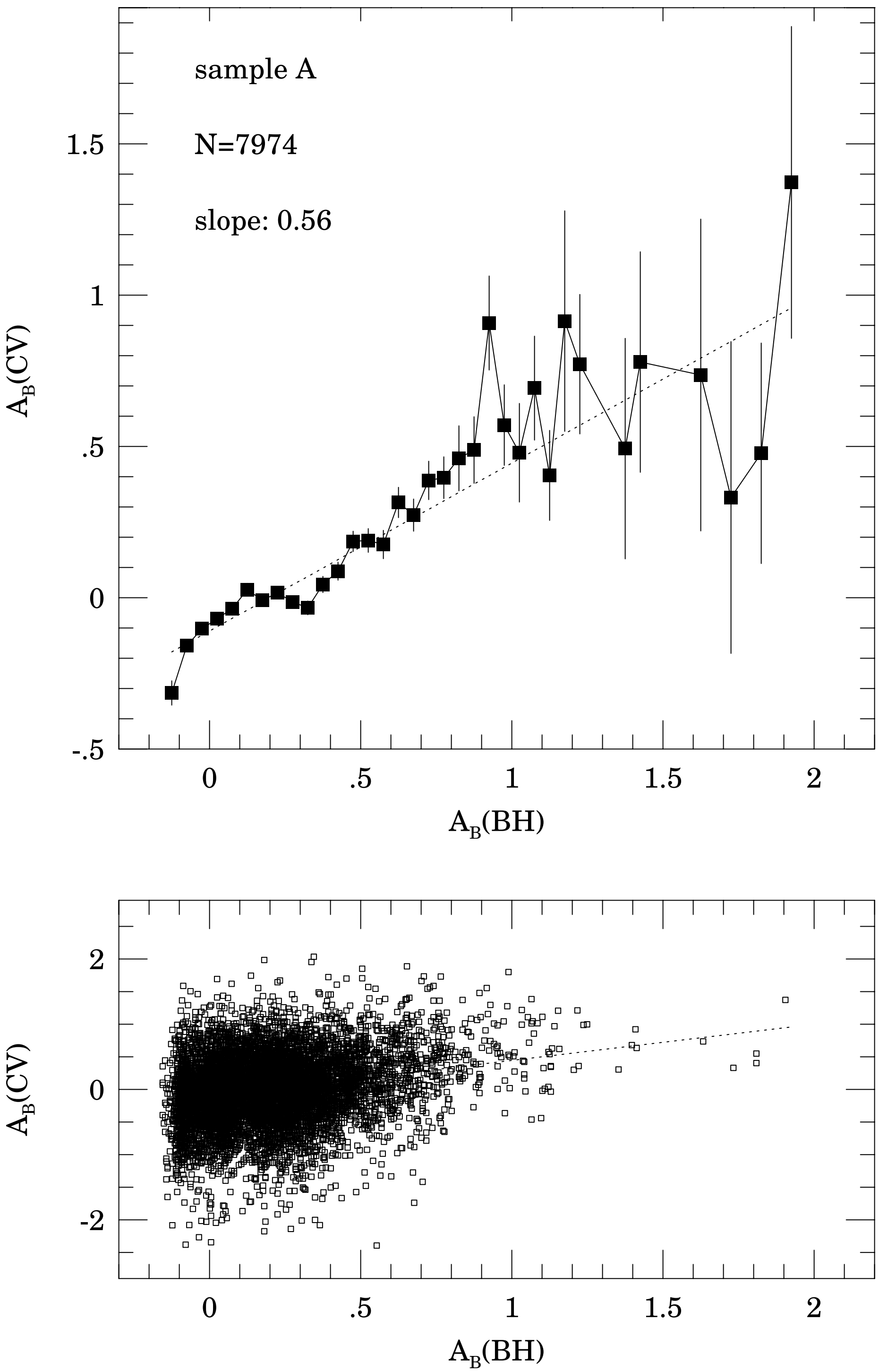

Figure 7. The same as Fig. 5 but for extinction of BH $A_B(BH)$.

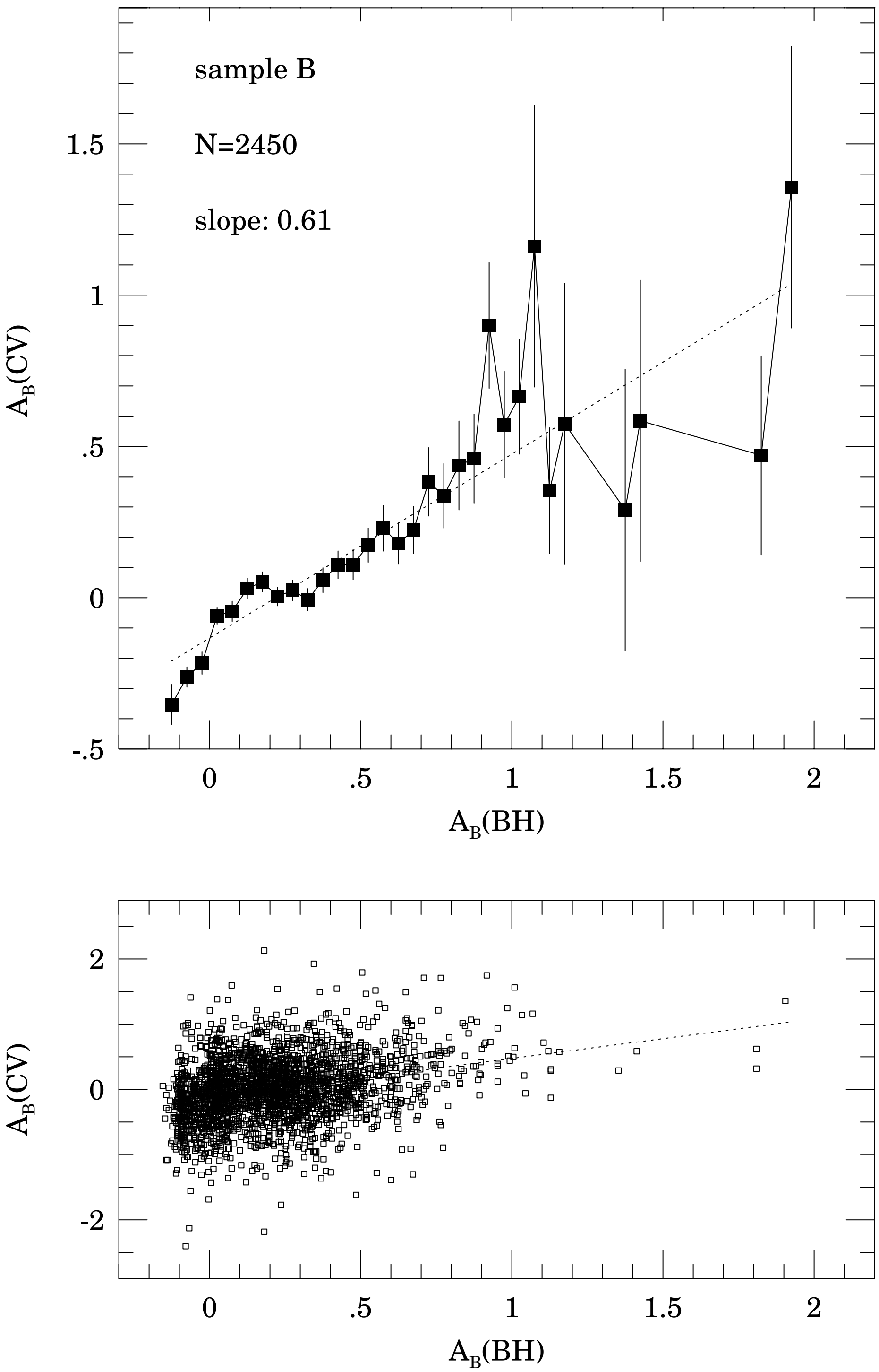

Figure 8. The same as Fig. 7 but for sample "B".

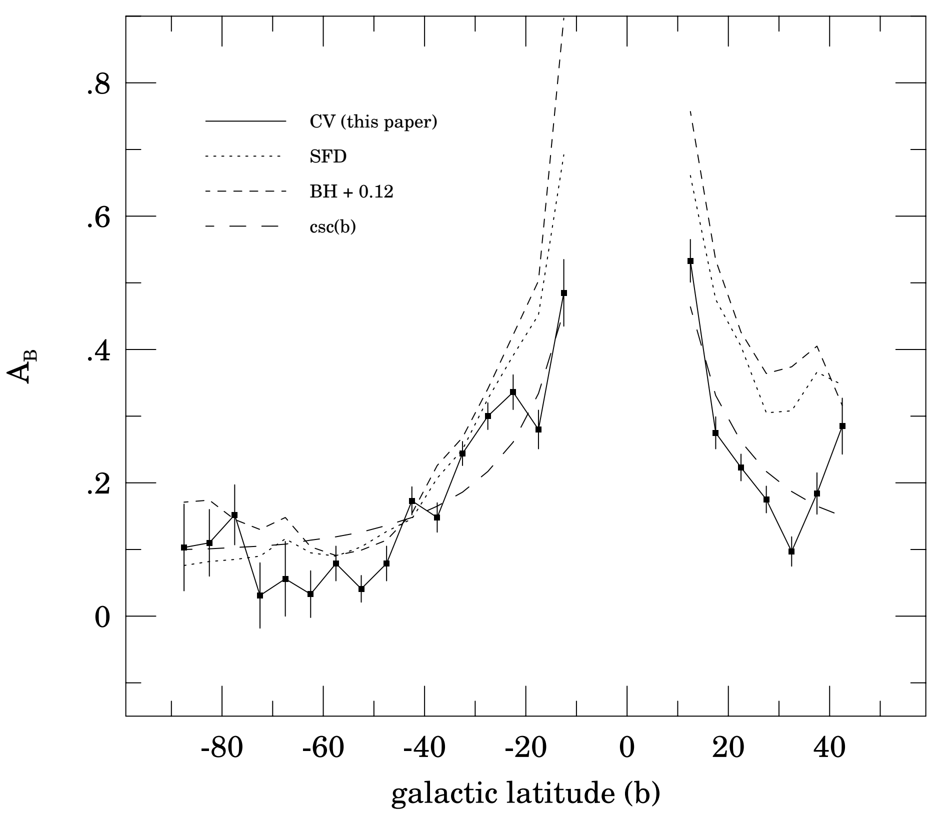

Figure 9. Galactic latitude dependence of our absolute extinction (represented by the solid broken line with 1σ error bars) compared with the extinction according to SFD, BH and the cosecans law. The BH extinction have been corrected by adding 0.12 magnitude constant. Note north-south assymetry of our extinction near the Galactic equator ($|b| < 40^o$) and non-zero extinction near the Galactic south pole ($b \approx -90$).

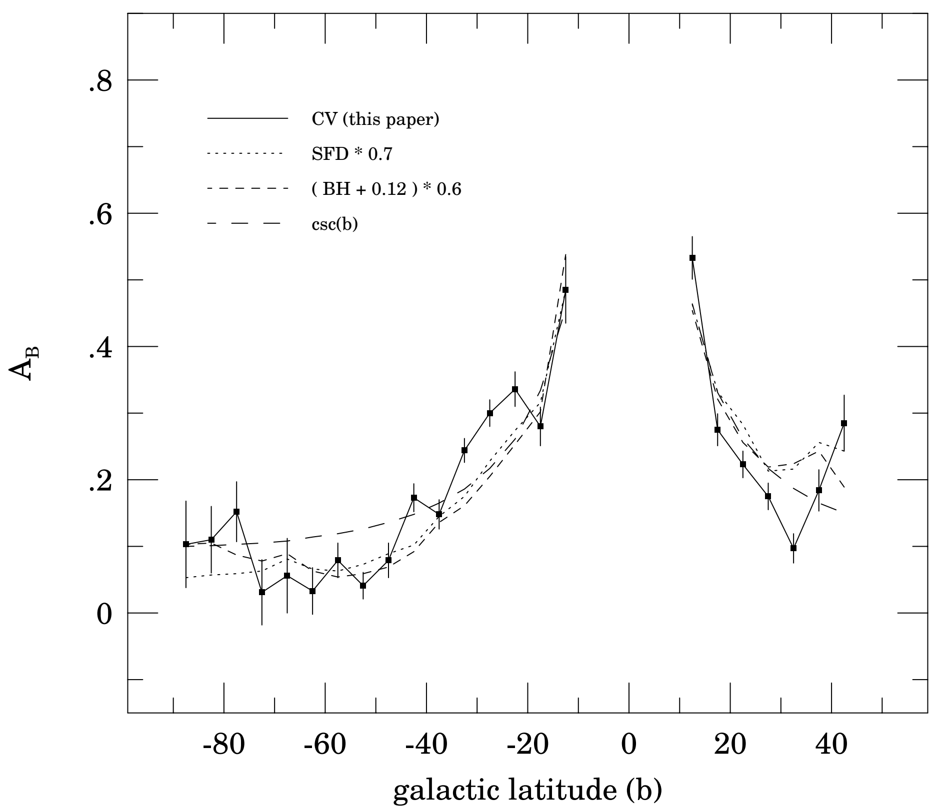

Figure 10. The same as Fig. 9 but with SFD extinction multiplied by the factor 0.7 and for corrected BH extinction multiplied by 0.6.